USE OF A SINGLE FINITE ELEMENT MESH FOR A STOP-G ANALYSIS FOR THE LISA SPACECRAFT

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ABSTRACT

The LISA mission is designed to measure gravitational waves using a large, space-based laser interferometry system. It consists of three identical spacecraft flying in an equilateral triangle formation with five million kilometers separating each spacecraft. Each spacecraft includes two free-floating proof masses, where the gravitational forces between the spacecraft and the proof masses must be balanced. If no external forces are applied to the proof masses, then the path length of the laser between them is known and fixed. A passing gravitational wave, however, would result in a change in the path length and would be detected by a change in the interference pattern using laser interferometry. However, movement of one of the proof masses would also result in a change in the laser path length and may be confused for a gravitational wave. Therefore, it is mission critical to minimize spacecraft forces on the proof masses.

In order to minimize spacecraft effects on the proof mass, LISA has strict thermal requirements, related to thermal distortions, which could unbalance the self-gravity characteristics of the design. As such, a STOP-G (**S**tructural, **T**hermal, **OP**tical, self-**G**ravity) analysis using a single, inter-disciplinary model is required to validate any design iteration. Therefore, it is foreseen to have a continuous feedback analysis effort requiring numerous individual STOP-G analyses. A primary goal of these analyses is to minimize error sources through all phases (including the passing of data among various disciplines).

To eliminate errors associated with temperature mapping between a thermal and structural model, it has been proposed to use a single finite element mesh for thermal, structural, and self-gravity analyses. While this will simplify model generation and consistency, it has drawbacks, since required detail in a thermal model is often quite different than that required by a structural model. Two thermal codes were investigated for their capability to generate temperatures from a spacecraft-representative, finite element model: ThermalDesktop® and TMG®. Thermal results were passed back to the structural analyst for thermal distortion analysis; thermal distortions were in turn passed to the self-gravity and optics analysts for further evaluation.

This paper presents lessons learned from this effort, using a single mesh for all disciplines in the STOP-G analysis. It should be noted that the goal of this effort was to ***test the process*** and results from these runs are in no way indicative of expected results from the LISA design. Through this process, strengths and weaknesses of each of the thermal codes were identified and are presented herein.

1 INTRODUCTION

LISA (**L**aser **I**nterferometer **S**pace **A**ntenna) is a joint NASA-ESA constellation mission to detect the presence of gravitational waves using laser interferometry scheduled to launch in 2011. Each spacecraft contains two free floating proof masses used as targets to reflect the corresponding spacecraft's laser signal. As such, strict requirements exist to minimize any forces that may affect movement of the proof mass (so as not to be confused as a gravitational wave). To satisfy the requirements, end-to-end STOP-G (**S**tructural-**T**hermal-**OP**tics-**G**ravity) analyses will need to be performed for any design or modification to evaluate its acceptability.

Due to the tight thermal requirements, unprecedented precision and accuracy is required for the thermal analysis. Efforts must be taken to reduce errors to all extents possible. Two potential sources of error in thermal analysis (independent of the model) have been identified: precision of numerical representation and errors introduced mapping temperatures from a thermal model to a structural model.

This paper describes the mission and thermal requirements for LISA and focuses on preliminary evaluation of the STOP-G analysis/data transfer process using a sample model. This task was performed for NASA/GSFC.

2 MISSION OVERVIEW

The LISA mission is designed to detect gravitational waves using laser interferometry. The mission consists of three identical spacecraft flying in a heliocentric orbit, 20° behind the Earth, in an equilateral triangle formation with 5 million kilometers separating each spacecraft. Each spacecraft is equipped with two laser/optical bench/proof mass assemblies. The design of the spacecraft requires that all components be gravitationally balanced about the proof masses to minimize spacecraft influences/disturbances on the proof mass.

2.1 MISSION DETAILS AND SCIENCE

For a gravitational wave to be detected, the two points in space (i.e. proof masses) between the laser must be stationary and the path length known. A passing gravitational wave causes a change in the path length between distant proof masses, detected by monitoring the resulting change in the interference pattern from the interferometer. The motion of the proof mass needs to be minimized, since this will also cause a change in the interference pattern and may be confused as a gravitational wave. As such, it is mission critical to minimize the forces acting on the spacecraft and the proof masses. Once injected into the science orbit, thermal distortions (as a result of a changing thermal environment or variations in dissipated power) may result in fluctuating forces on the proof mass. As such, the thermal design plays a large role in the success of the LISA mission. Figure 1 shows the current LISA design with the solar array and top plate removed for visibility.

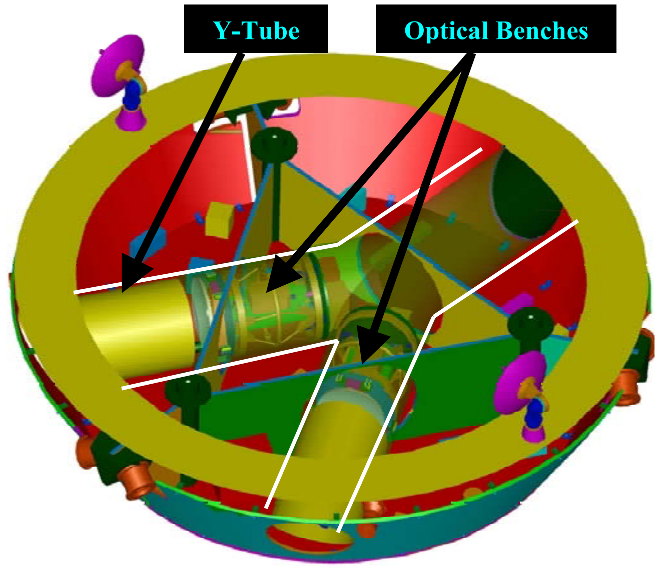

Figure 1 – LISA Spacecraft (Solar Array removed)

2.2 THERMAL REQUIREMENTS

The thermal requirements fall into two categories: fluctuations within a particular frequency range (that may be interpreted as a gravitational wave) and temperatures that may cause component misalignment on the optical bench. The area of primary concern is temperature fluctuations that may cause the proof masses to move and appear to the sensors as a gravitational wave. The requirements are stated in terms of temperature fluctuations per root Hertz and should be evaluated by transforming a time varying temperature profile into the frequency domain and calculating the power spectral density.

2.3 THERMAL DESIGN

The thermal design is to minimize thermal fluctuations that could affect the optical bench and components close to the proof mass. Since gravitational forces are higher for closer objects, fluctuations in temperature (and consequently thermal distortions) further away from the proof mass are less of an influence than fluctuations of closer components. Two potential sources of thermal fluctuation have been anticipated: variation in the solar intensity and fluctuation in on-board power dissipations. To minimize the effects of both of these, various layers of conductive and radiative isolation exist throughout the heat paths internal to the spacecraft.

The solar array is isolated from the spacecraft structure using low conductivity stand offs and insulating foam in a honeycomb panel. This first layer of isolation allows very little of the absorbed solar heat to transfer through to the spacecraft. The second layer of isolation is achieved by using low conductivity mounts and goldized coatings to minimize radiation from the spacecraft to the Y-Tube (external) and from the Y-Tube (internal) to the thermal shield. Lastly, the thermal shield is also goldized to minimize heat transfer to the optical bench. Due to an inability to ground test and include self-gravity effects, the LISA project will rely heavily on highly accurate, analytical efforts.

3 ANALYSIS AND DATA TRANSFER PROCESS

The goal of future analysis efforts for LISA will be to verify any potential design. This will be done using a STOP-G analysis campaign to validate any design for its acceptability with respect to thermal, distortion, and self-gravity requirements. In anticipation of a large number of these analyses, it is imperative to streamline the process and minimize turn-around time and errors associated with data exchange.

3.1 STOP-G ANALYSIS

The STOP-G process begins from a single Finite Element Model (FEM) and propagates results through four, inter-dependent discipline analyses to validate a design. The process begins with the thermal analysis, which consists of generating temperature predictions throughout the model. These nodal temperature results are then passed to the structural engineer to determine the thermal distortions as a result of thermal effects. These distortions are then passed in parallel to the optics engineer and the self-gravity engineer. The optics engineer uses the distortions to determine if any unacceptable misalignment of optical components occurs. The self-gravity engineer determines the self-gravitational effects and evaluates if the forces and gradients are within acceptable parameters. The process may result in a design change, which requires executing the entire process again, since small changes in temperature may have a large effect on the self-gravity.

Figure 2 shows the STOP-G data analysis flow, beginning with a solid model from IDEAS® brought into FEMAP® to be meshed. This single mesh is then exported to NASTRAN® for structural modeling, and TMG® and/or ThermalDesktop® for thermal modeling. The format used for the data transfer is shown beside each path.

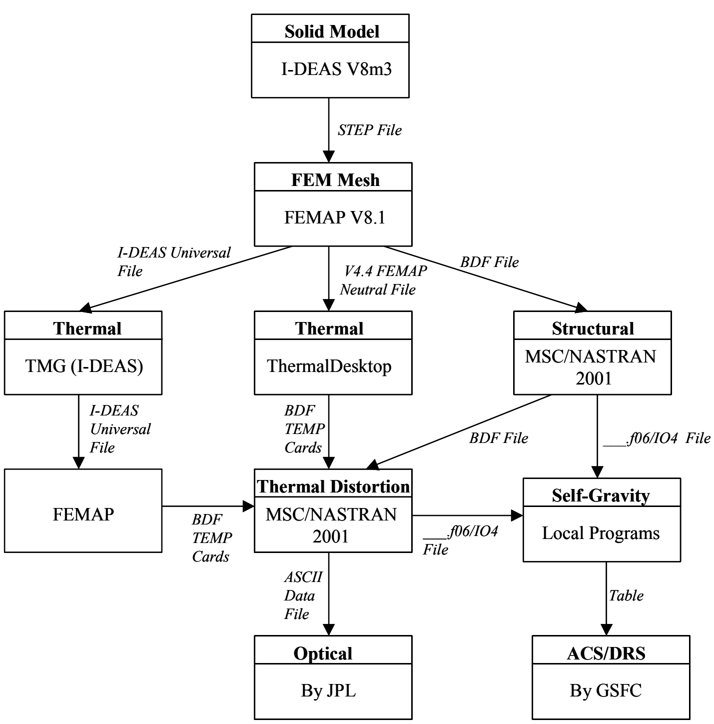

Figure 2 – Original STOP-G Data Analysis Flow

3.2 THERMAL SOFTWARE EVALUATION

Two thermal codes were evaluated that are capable of analyzing both the radiation and thermal portions required by the STOP-G analysis: TMG® (by MAYA HTT) and ThermalDesktop® (by Cullimore and Ring). The end goal of the analysis is to produce temperatures for the corner nodes defining the elements to be passed to the structural analyst. Both of these codes solve for temperatures in double precision (32 bit), which represents the best precision available with commercial codes. Each of these codes has both advantages and disadvantages in their ability to generate accurate nodal temperature results in a timely manner, which will be further discussed below.

3.2.1 THERMAL MODEL GENERATOR (TMG®)

TMG® typically generates diffuse view factors (Fij) for the radiation portion of the solution. Two methods are available (an analytical method and the Hemiview method), both based on a Nusselt Sphere solution. The analytical solution is a computational routine that generates view factors but was found to be too slow on the platform available at the time. The Hemiview method is a graphics enabled solution that very rapidly solves for the diffuse view factors. Specular behavior can be modeled using a deterministic ray tracing algorithm and updating diffuse view factors with specular interchange factors (Bij) determined from the ray trace. However, the benefits of a quick diffuse solution may decrease if many specular effects need to be calculated.

For the conduction (i.e. thermal) problem, TMG® uses a finite volume formulation to generate a finite difference solution, with the finite volume defined by the element boundaries. Arithmetic, mid-side nodes are introduced internally to handle conduction between elements. Heat loads, radiative couplings, and capacitance are lumped at the centroid of the element and a system of equations generated. Temperatures are solved for the centroid and mid-side nodes and extrapolated to the corner nodes, possibly introducing a source of error. The resulting network for a 3-element sample is shown in Figure 3.

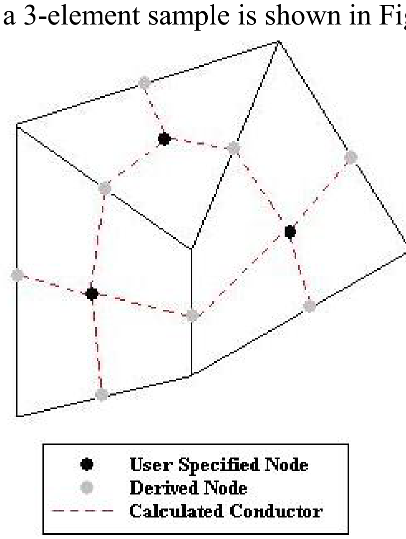

Figure 3 – TMG® Conduction Formulation

3.2.2 THERMAL DESKTOP®

ThermalDesktop® uses the well-known Monte Carlo Ray Trace (MCRT) solution to generate both Bij's and heat loads. Shape functions are used to apportion energy associated with each ray to the corner nodes based on proximity of the ray location to the node. No distinction needs to be made for diffuse versus specular solutions, since the MCRT accounts for specular and diffuse behavior throughout its solution. However, the error associated with any Bij increases with smaller Bij's and smaller numbers of rays. This requires a very large number of rays to be sampled when using a highly detailed, finite element model and could result in very long computation times.

ThermalDesktop® uses a finite element formulation to generate a finite difference compatible solution. Shape functions are used to apportion element capacitance, conductance, and applied heat loads to the corner nodes. Temperatures are solved at the corner nodes, thereby eliminating the temperature extrapolation necessary with TMG®. The resulting network for a 3-element sample is shown in Figure 4.

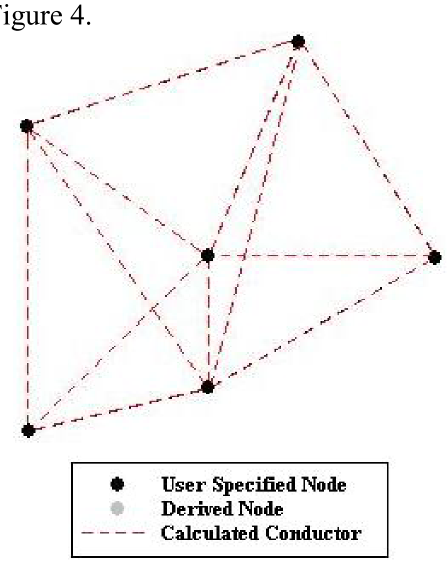

Figure 4 – ThermalDesktop® Conduction Formulation

3.2.3 LESSONS LEARNED

The Hemiview method for TMG® is ***very*** fast for the calculation of diffuse view factors. However, if specular effects are deemed important, then the quick calculation of diffuse view factors is of diminishing return.

The temperature extrapolation/interpolation for TMG® from mid-side and centroid nodes to corner nodes introduces a source of error. This error is larger for external nodes than for internal nodes (which are connected to multiple elements) and is the worst for nodes connected only to a single element.

The MCRT in ThermalDesktop® is the most accurate method for calculating interchange factors, but its accuracy is a direct function of the number of rays sampled. For smaller Bij's (which are often present in FE models), a large number of rays should be sampled.

The conduction formulation for ThermalDesktop® results in "conductor" terms that no longer represent a simple conductance between two points. Therefore, evaluation of heat flows are much more difficult than with a true finite difference set of equations. However, the temperatures are solved for the corner nodes, eliminating any error associated with temperature mapping.

In summary, TMG® can generally calculate radiative exchange factors faster than ThermalDesktop®; however nodal temperature results are less accurate due to the internal temperature mapping.

3.3 SAMPLE FINITE ELEMENT MODEL

A sample model (based on the ESA FTR design) was developed to evaluate the feasibility of using a single topology mesh for the LISA STOP-G process. To date, most STOP analyses have used three models (i.e. 1 structural, 1 thermal, and 1 optical) having unique topologies (i.e. discretization schemes). However, parallel development of the thermal, structural, and optical models can lead to errors ranging from differences in the configurations being modeled to interpolation/extrapolation errors associated with mapping results between dissimilar meshes. Use of a single mesh by all disciplines will eliminate errors associated with mapping temperature data from a coarse thermal model to a detailed structural model. The sample model would also test the ability to transfer data between and among disciplines on a model similar to the LISA design, without the need for stringent model review prior to a typical analysis campaign.

3.3.1 FINITE ELEMENT DISCRETIZATION

The final model topology, based on a solid CAD representation, is chosen so that the structural, thermal, optical, and self-gravity analyses can be performed with the requisite accuracies and precisions. Developing the spacecraft FEM depends on constant interaction between the structural, thermal, self-gravity, and optical analysts during the mesh generation and is the basis for making decisions related to the abstraction/exclusion of features, determination of acceptable element types and qualities, and node locations/mesh density. Upon development of the sample, model it was necessary to include a verification step to allow the thermal, optical, and self-gravity engineers to confirm the model will meet their analysis needs. The purpose of this is to reduce unnecessary re-meshing efforts.

The primary intent of the sample model generation was process evaluation and not accuracy of results. As a result, a relatively coarse mesh of the LISA science module was developed and is shown in Figure 5. The FEM contained 14101 elements and 10563 nodes. Nonstructural components (solar arrays, electronics boxes, antennas, etc) were not included in this model in order to keep the model simple and to reduce modeling time and DOF. Before meshing this model, several meetings were held between engineering disciplines to discuss modeling techniques to verify the model would meet the needs of all disciplines.

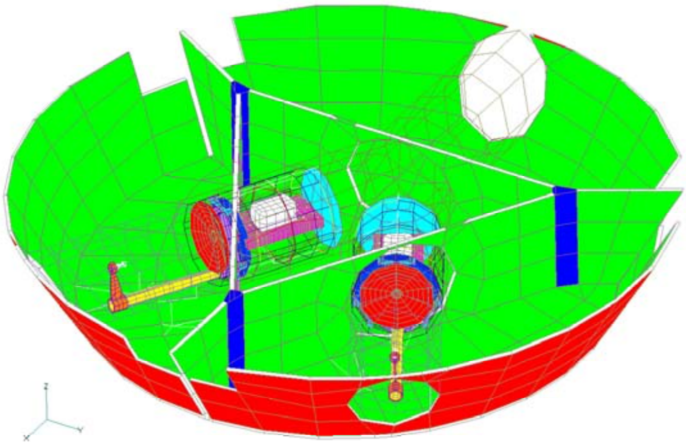

Figure 5 – Sample FEM (Top panel removed)

Self-gravity analysts agreed to use the mesh size selected by the other disciplines; however, recent analysis has led to the development of self-gravity mesh size guidelines. Although this model is not explicitly used for optical analysis, the distortion output is. In order to avoid mapping errors between this model and the optical model, nodal locations for the optical components in the sample FEM were obtained directly from the optical analysts.

The greatest challenge was satisfying the thermal analysis needs, which required 2D (plate) elements for all radiating surfaces. This necessitated the addition of zero thickness shell coatings on the exterior of solid elements and compromises to be made for 1D (line) elements. It also required the addition of plate elements for components typically represented in the model as point masses (e.g. electronics boxes, antennas, etc.). Meeting these thermal needs may become more difficult as the size and complexity of the model increases. Element orientation was also important to the thermal analysts to correctly model optical properties and radiating sides of elements.

To complete the STOP-G process evaluation and feasibility study of a single mesh topology, the sample model was run through the complete STOP-G analysis cycle. Nodal temperature predictions from the thermal analysis were calculated using both ThermalDesktop®-SINDA/FLUINT and TMG®. This aided in the parallel study of the capabilities and accuracies of these two CAE tools. The temperature profiles from both thermal analysis tools were then used to obtain spacecraft distortions. These distortions were then passed on to the optical analysts and self-gravity analysts to familiarize them with the format in which data will be provided for future STOP-G analysis cycles. Results from this sample STOP-G cycle are not presented since the focus of this work was process evaluation and not accuracy of results. However, valuable lessons concerning the process of using a single topology model for interdisciplinary analysis were learned during this evaluation and are further discussed below.

3.4 LESSONS LEARNED

Building a spacecraft model with a common topology requires input from all disciplines so that the final model meets the needs of each discipline. As a result, the model will likely be larger and more detailed than any one analyst would employ to meet the needs of their discipline.

Electronics boxes and other nonstructural components, typically neglected in structural distortion analysis, will have to be included because they contain radiating surfaces that will contribute to the temperature profile.

Exterior faces of solid elements will have to be shell coated with thin, "dummy" plate elements to account for radiation. Special consideration will have to be given to bar elements representing components that may need to have surface area to model radiation.

Element normal directions are important to determine which sides of elements participate in radiation exchange (activity) and to identify proper assignment of thermo-optical properties.

Optical component locations must be included in the FEM as provided by the optical analysts to increase model accuracy and avoid re-mapping errors.

Smaller mesh size nearer to the proof mass is more important than mesh size further away from the proof mass.

If TMG® is used as the thermal solver, material numbers should be less than 10,000 to comply with the IDEAS® Universal File format.

A formal procedure should be implemented for the acceptance of a mesh by all disciplines prior to start of an analysis campaign. Figure 2 should be revised to Figure 6.

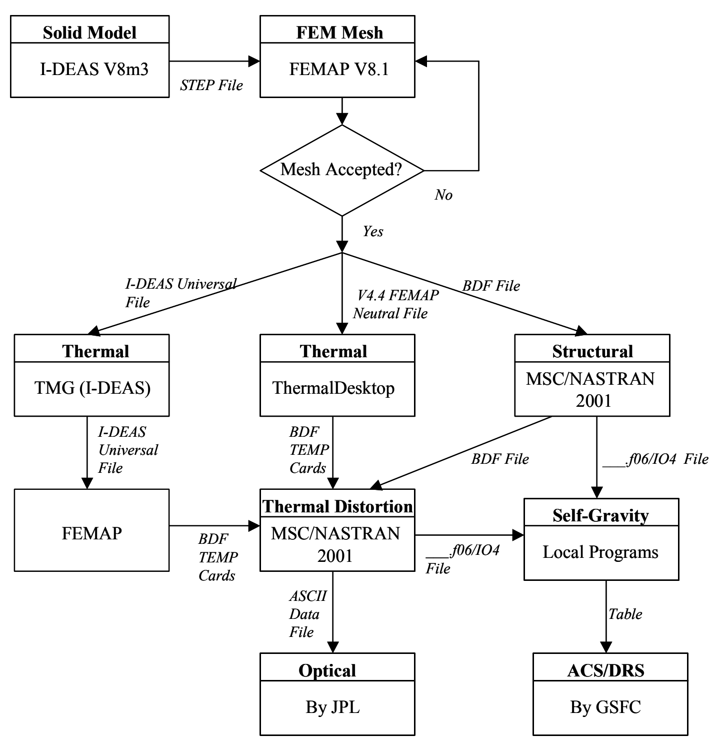

Figure 6 – Updated STOP-G Data Analysis Flow

4 CONCLUSIONS

Strict requirements, along with the inability to include self-gravity effects in ground tests, result in the need for unprecedented precision and accuracy in analysis. Efforts must be taken to reduce errors to all extents possible using highly accurate, interdisciplinary STOP-G analyses. These analyses will be used to evaluate any LISA design for its acceptability with respect to thermal, distortion, and self-gravity requirements.

Since the only expected fluctuations in on-orbit forces are due to thermal effects, special attention needs to be given to the software used for the thermal portion of the STOP-G analysis. Two thermal codes were evaluated that are capable of analyzing both the radiation and thermal portions required by the STOP-G analysis: TMG® and ThermalDesktop®.

"Model-independent" sources of error include: available numerical precision and temperature mapping. Both of these codes solve for temperatures in double precision (32 bit), which represents the best numerical precision available with commercial codes. Using a single mesh for all phases of the STOP-G analysis eliminates the temperature mapping error. TMG®, however, includes an inherent mapping from its temperature calculation points to the nodal locations. ThermalDesktop® has a slight advantage, since it directly calculates nodal temperatures without the need for interpolation/extrapolation, but at the cost of analysis time. At this phase of the LISA project, ThermalDesktop® has been selected for the next analysis campaign, but the decision may be re-evaluated as both codes are investigated further.

A sample model was evaluated to test the analysis/data transfer process and yielded valuable lessons learned for the next analysis campaign. Inclusion of additional elements and specific mesh locations may be needed to satisfy the needs of the thermal and optical subsystems. It is also highly recommended to have a thorough review of any mesh generated by all disciplines prior to beginning an analysis campaign to eliminate unnecessary mesh regeneration.

5 FUTURE WORK

The review process will continue to be streamlined so that the structural engineer responsible for the mesh generation will be able to anticipate the requirements and needs for each discipline. The solid model is currently under final review including all the components of the FTR design and will be then meshed. The mesh will be reviewed by the Thermal, Structural, Optics, and Self-Gravity disciplines, and the next STOP-G analysis campaign will begin. This campaign will be better able to focus on accuracy of the results and a comparison of results produced by ThermalDesktop® and TMG® based on a more realistic mesh.

REFERENCES

The following papers contain additional information about the current design of LISA and the STOP-G process

- "LISA Final Technical Report", Astrium GmbH, April 2000
- SAI-RPT-532, "The LISA STOPG Analysis Process, with a Sample Problem and Lessons Learned", Swales Aerospace, June 5 2003

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ACRONYMS

NASA	National Aeronautics and Space Administration
ESA	European Space Agency
GSFC	Goddard Space Flight Center
LISA	Laser Interferometer Space Antenna
STOP-G	Structural, Thermal, Optics, Self-Gravity
FEM	Finite Element Model
FE	Finite Element
DOF	Degree of Freedom
TMG	Thermal Model Generator
MCRT	Monte Carlo Ray Trace
CAE	Computer Aided Engineering
CAD	Computer Aided Design
FTR	Final Technical Report